Motor vehicle emission inventory for the Perth airshed

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Abstract

A motor vehicle emission inventory is developed for the Perth metropolitan airshed by integrating data on traffic flow conditions with emission factors that incorporate the effects of both speed and acceleration. This highlights the impact of varying driving conditions on the spatial and temporal resolution of vehicle emissions, and illustrates that traffic congestion enhances pollutant production through increased variations in vehicle accelerations

Introduction

Air quality within Perth is for most days of the year exceptionally clean when compared to cities of comparable size (Bottomley & Cattell 1974, Lax *et al* 1986). However under suitable meteorological conditions pollution events can occur that exceed the USA primary and secondary standards (Bottomley & Cattell 1974, KAMS 1982). These are generally associated with light stable synoptic pressure gradients (Bottomley & Cattell 1974) or mesoscale phenomena, such as the sea breeze (KAMS 1982)

With Perth, the emission of gaseous pollutants is confined to two major sources: an industrial area concentrated to the southwest of the metropolitan area and motor vehicles within the region (Lax *et al* 1986). The Kwinana industrial area emits large quantities of SO_2 and to a lesser extent NO_x (KAMS 1982). These emissions have been modelled under both stable conditions (Kamst & Lyons 1982) and sea breeze fumigation (KAMS 1982), as well as in a standard climatological model based on Gaussian techniques (KAMS 1982). In all cases, the models applied to the immediate region surrounding Kwinana and did not attempt to incorporate the broader airshed concept.

An analysis of the air quality across the broader metropolitan airshed requires the estimation of the other major source outside the industrial area, motor vehicles. These are the source of oxides of nitrogen (NO_x), brake lining dust, hydrocarbons (HC), carbon monoxide (CO), smoke, aldehydes, lead salts and particles, rubber, gaseous petrol and carbon particles (Lay 1984). All of the CO and NO_x are emitted from the exhaust pipe whereas approximately 50% of the HC's from an uncontrolled vehicle are emitted via the exhaust, with the remainder coming from the crankcase, carburetor and fuel tank vents (SPCC 1980).

Evaporative emissions result from the fuel system leaking HC's to the atmosphere at a rate determined by the temperature of the system (diurnal emissions) and hot soak emissions occuring after the vehicle has been driven some distance, through heating of the carburetor and fuel lines (Nelson 1981). Hamilton *et al* (1982) estimated evaporative emissions from typical early 1970's vehicles as 0.8 g km^{-1} and noted that these are generally constant through the life of the vehicle. Subsequent to 1975, Australian emission standards (Table 1) have resulted in improved pollution control, as evidenced by Nelson (1981). He confirmed diurnal evaporative emission factors of 22.1 g $vehicle^{-1}$ day^{-1} for uncontrolled (pre 1975), and 5.1 g $vehicle^{-1}$ day^{-1} for controlled vehicles, respectively, with hot soak emissions of 12.5 g $vehicle^{-1}$ for uncontrolled, and 4.2 g $vehicle^{-1}$ for controlled vehicles. Consequently, evaporative emissions are a function of the age of the fleet whereas exhaust emissions are also dependent on vehicle driving characteristics. Hence the spatial and temporal variation of emission source strength is dependant on driving chracteristics across the airshed as well as the age mix of the fleet.

Table 1

Australian emission standards, g km^{-1}. (after SPCC 1980)

	Date of Manufacture After 1 July 1976	After 1 January 1981
CO	24.2	18.6
HC	2.1	1.75
NO_x	1.9	1.9

Vehicle emissions in Sydney were estimated by Stewart *et al* 1982 from the product of vehicle kilometres travelled (VKT), emissions per kilometre for each model year and travel fraction done by each model year. Although this gives a bulk estimate across the airshed it does not allow for the spatial resolution of the sources nor does it account for variations in driving conditions.

From a preliminary dynamometer test of 28 vehicles, Kent & Mudford (1979) found that typical emissions under Australian urban driving conditions, at that time, could be expressed as:

$$[CO] = 465s^{-0.97}$$
$$[HC] = 21.5s^{-0.73}$$
$$[NO_x] = 2.2 + 0.008s$$

where [CO] is the carbon monoxide emission (g km^{-1}), [HC] hydrocarbon emission (g km^{-1}), [NO_x] oxides of nitrogen emission (g km^{-1}) and s the average vehicle speed (km h^{-1}). These are of a similar form to the estimates used by Iverach *et al* (1976), based on US experience, and equivalent to the values employed by Taylor & Anderson (1982).

Such an estimation assumes emissions can be represented in terms of average speed alone and neglects the influence of variations in driving conditions, particularly changes in acceleration, on emissions. For example, Kent & Mudford (1979) found that a three dimensional plot of emission rates against speed and acceleration led to parabolic surfaces for CO and HC's, while NO_x showed a general increase in emission rates with speed and acceleration. In particular, they found that both CO and NO_x show marked increases in emission rate with positive acceleration. This cannot be accounted for from an average speed model and highlights the need to incorporate a wide range of accelerations and speeds to produce reasonably representative emission inventories.

Thus the spatial resolution of these emissions requires an integration of data concerning traffic flow characteristics with data on vehicle numbers, vehicle types and VKT. Previous work in this area has emphasized the latter data on vehicles and has lacked any detailed input about how those vehicles are being driven (SATS 1974, Visalli 1981). A very basic approach to incorporate driving patterns has been attempted for Melbourne but uses only the standard Los Angeles driving cycle for its traffic characteristics (Neylon & Collins 1982).

Hence this paper addresses the development of a motor vehicle emissions inventory for the Perth urban area based on actual driving pattern data across the urban area as well as vehicle emission data resolved on the basis of speed and acceleration. Pollutant source strengths are expressed as the total emission averaged over a specified time period and a specified grid square of the airshed.

Methodology

Kenworthy *et al* (1983) used an urban ecological approach in treating the city as an integrated system, to obtain representative driving cycles across Perth. They div-

Table 2

A summary description of the six driving pattern areas in terms of the major factors used to derive them (after Kenworthy *et al* 1983). Note all rankings of characteristics are made relative to the mean of Perth.

Characteristics / Area	Social Economic Status of Residents (Household income and vehicle ownership)	Activity Intensity of area (land use intensity, congestion, public transport availability)	Dominant modal split features of residents
Central Core Area 1	Very low	Very high	Peak periods Very low private vehicle usage, very high public transport, walking and biking
Inner suburbs Area 2	Average to low	High	All periods Very high public transport
Middle Western suburbs Area 3	Average to high	Average to high	Off peak Very low public transport usage
Middle South, outer North and Eastern suburbs Area 4	High	Low	Peak periods High private vehicle usage, low public transport, walking and biking
Outer South East and North East suburbs Area 5	Average	Very low	Off peak Very high private vehicle usage, very low walking and biking
Northern State Housing suburbs Area 6	Low	Average to low	Off peak Very low private vehicle usage, very high walking and biking

ided the metropolitan area into six regions characterized in terms of socio-economic status and activity intensity (Table 2), and using the chase car technique (Scott Research Laboratories 1971) obtained detailed second by second speed time histories of typical urban driving in each of these regions. Although statistically representative driving cycles can be generated from such data, they suffer a considerable loss in speed resolution (Lyons *et al* (1986). Hence, Kenworthy *et al* (1983) obtained representative driving cycles for each region by matching summary characteristics to the observed speed time traces, which is consistent with the methodology adopted by Kuhler & Karstens (1978). Accordingly, they obtained the representative urban driving speed time traces summarized in Table 3, for morning peak (MP), evening peak (EP) and off peak (OP) periods for each region.

These speed time traces were converted into speed acceleration probability matrices, where each matrix cell, of size 5 km h^{-1} by 1 km h^{-1} s^{-1}, contains the total number of one-second observations in the respective range from the representative driving cycle. Thus each matrix element represents the total time during the representative driving cycle that the vehicle was at that speed and acceleration.

Post *et al* (1985) extended the analysis of Kent & Mudford (1979) to 177 Australian light duty vehicles in use, and obtained fleet averaged emission rates as a function of vehicle velocity and acceleration. Their results are presented at the same resolution as the speed acceleration probability matrices. Since cell averaged emission rates are independent of the velocity profile followed by the vehicle (Post *et al* 1981a,b), these can be used to estimate emissions for any driving pattern, assuming that the vehicles used by Post *et al* (1985) are representative of the typical Australian urban fleet. Hence the total emissions over a representative driving cycle can be expressed as

$$[P] = \sum_{i=1}^{n} \sum_{j=1}^{n} e_{i,j}\, t_{i,j}$$

where [P] is the emission (g) of pollutant species P, $e_{i,j}$ is the emission rate (g s^{-1}) of pollutant species P for the matrix element defined by velocity i and acceleration j (Post *et al* 1985), t_{ij} total time(s) vehicle spent at that velocity and acceleration during the driving cycle and the summation is over all possible speed acceleration cells. [P] is the total emission over the period of the driving cycle. Hence the characteristic emission factor (g km^{-1}) for that driving cycle can be represented as

$$[P]_k = [P] / d_k$$

where d_k is the distance covered during the driving cycle (see Table 3).

Table 3

Characteristics of representative driving cycles for each area and time period, where MP is morning peak, OP off peak and EP evening peak

Area	Dist. from CBD (km)	Aver. Speed (km h^{-1})	RMS Accel. (m s^{-2})	Stops per km. (km^{-1})	Idle Time (%)	Cruise Time (%)	Distance d_k (km)
1	2						
MP		30.0	0.89	1.60	20.6	13.8	11.9
OP		35.1	0.86	1.43	15.6	13.7	11.9
EP		30.6	0.87	1.60	18.4	12.5	11.9
2	5						
MP		36.4	0.80	1.39	17.9	27.5	14.5
OP		43.1	0.82	0.84	9.6	38.3	14.2
EP		38.8	0.85	0.95	17.9	30.3	16.8
3	9						
MP		40.6	0.78	0.79	11.4	30.8	17.7
OP		46.7	0.70	0.45	5.3	35.5	17.8
EP		45.3	0.71	0.56	8.2	38.5	17.7
6	11						
MP		42.4	0.74	0.72	13.3	36.7	19.4
OP		47.4	0.76	0.54	11.3	44.7	20.3
EP		45.2	0.76	0.64	14.4	49.5	20.3
4	13						
MP		37.6	0.77	1.08	14.3	30.6	19.4
OP		46.8	0.80	0.67	10.1	46.7	19.4
EP		41.1	0.76	0.82	18.3	33.7	19.4
5	19						
MP		52.9	0.69	0.33	3.4	59.4	18.4
OP		52.0	0.70	0.27	3.6	55.2	18.3
EP		50.0	0.78	0.30	4.6	54.9	19.8

Within Australia, exhaust emission rates for CO and NO_x for heavy duty diesel powered vehicles remain uncontrolled and no locally validated data was readily available. Emission rates based on US experience and assumed independent of vehicle speed are listed in Table 4 (Stern 1976, USEPA 1977). These represent uncontrolled emissions averaged over a number of vehicles, operating under a variety of conditions, and are consistent with the heavy duty emission rates used by Jakeman *et al* (1984) for Australian conditions. Luria *et al* (1984) obtained similar values for buses and expressed the emission factors for NO_x, HC and CO as a function of speed. They showed a marked decrease in CO and HC emissions with speed and an increase in NO_x emissions up to a speed of 40 km h^{-1}. In the absence of alternate emissiun factors these were used.

Trucks within the Perth metropolitan area are mostly able to maintain easy cruise conditions and appear to avoid built up areas and peak conditions (Lyons *et al* 1987). Unlike automobiles, their driving cycle shows no dependence on location or time period. Consequently, as the heavy duty diesel emission factors are only expressed as a function of speed, the average speed from the Perth truck driving cycle of 43.2 km h^{-1} (Lyons *et al* 1987) was assumed for all truck emissions, leading to the emission factors shown in Table 4.

Table 4

General emission factors (g km^{-1}) for heavy duty diesel powered vehicles (after [1]Stern 1976; [2]USEPA 1977) and those used in this study assuming an average speed of 42.3 km h^{-1} (after [3]Luria *et al* 1984).

Pollutant	Emission factor g km^{-1} (1, 2)	(3)
Particulates	0.8	
CO	17.8	9.5
HC	2.9	1.5
NO_x	13.0	10.2
Aldehydes	0.2	
Organic acids	0.2	
SO_x	1.7	

The total emission in any period and any area of the city can be expressed as

$$E = \sum_{m=1}^{n} [P]_{k,m} VKT_{k,m}$$

where $[P]_{k,m}$ and $VKT_{k,m}$ are the emission factor and total VKT, respectively, for that time period and area and the summation is over vehicle type.

Results and Discussion

Combining the characteristic driving patterns (Kenworthy *et al* 1983) and the fleet emissions (Post *et al* 1985) led to the automobile emission factors shown in Table 5 for each of the representative areas. As these factors are based on the same fleet data, the differences are directly attributable to the style of driving in each of the areas. This emphasizes the contribution of variations in speed and acceleration patterns across a metropolitan area in determining the spatial variation of emissions.

Table 5

Emission factors g km^{-1} for exhaust emissions for each time period and region based on speed acceleration matrix.

Area	1	2	3	6	4	5
NO_x						
MP	1.9	1.8	1.8	1.7	1.9	1.7
OP	1.9	1.9	1.7	1.8	2.0	1.7
EP	1.8	1.8	1.8	1.9	1.9	1.8
CO						
MP	21.8	18.4	18.1	16.9	19.2	14.8
OP	19.2	17.4	15.7	15.9	16.8	15.2
EP	21.3	18.5	16.7	16.9	17.5	16.0
HC						
MP	2.2	1.9	1.9	1.8	2.0	1.8
OP	2.0	1.8	1.7	1.8	1.8	1.7
EP	2.2	1.9	1.8	1.9	1.8	1.7

The corresponding automobile emission factors based solely on average speed in each of the regions (Table 3) are shown in Table 6. With the exception of the NO_x emission factors, the average speed factors are lower, as would be expected, since the incorporation of acceleration leads to greater variability in the driving patterns and hence higher emissions. The NO_x emissions are higher because the average speed equation implies a speed independent emission of 2.2 g km^{-1} (Kent & Mudford 1979) compared to the idle emission of 0.039 g min^{-1} of Post *et al* (1985). Their results also suggest that emissions of the order of 2.2 g km^{-1} are only observed under high acceleration which is not maintained for any length of time in representative urban driving cycles (Lyons *et al* 1986).

Table 6

Emission factors (g km^{-1}) for exhaust emissions for each time period and region based on average speed.

Area	1	2	3	6	4	5
NO_x						
MP	2.4	2.5	2.5	2.5	2.5	2.6
OP	2.5	2.5	2.6	2.6	2.6	2.6
EP	2.4	2.5	2.6	2.6	2.5	2.6
CO						
MP	17.2	14.2	12.8	12.3	13.8	9.9
OP	14.7	12.1	11.2	11.0	11.2	10.1
EP	16.8	13.4	11.5	11.5	12.7	10.5
HC						
MP	1.8	1.6	1.4	1.4	1.5	1.2
OP	1.6	1.4	1.3	1.3	1.3	1.2
EP	1.8	1.5	1.3	1.3	1.4	1.2

Within Perth, areas 1 and 5 illustrate the greatest differences in activity intensity ranging from the congested CBD, with its greater reliance on public transport, to the private vehicle dominated outer suburbs. Emission factors, based on the speed/acceleration distribution, show a decrease in emission factor between the CBD and the outer suburbs for NO_x corresponding to decreased accelerations characterised by high average speeds and maintained cruise conditions. Alternatively, emission factors based solely on average speed illustrate an increase as you move away from the congested CBD. Thus, a simple average speed model suggests higher emissions away from the congested CBD by not accounting for the marked acceleration changes induced by the congested stop start driving of the CBD.

The Perth metropolitan region was divided into grid squares of 1 km by 1 km and estimated daily VKT for each of these was obtained from traffic count information collected by the Main Roads Department (MRD 1986). Automatic traffic counts, of 1-3 days duration, are carried out on all major roads in the region, as well as points on these at which a change in volume might be expected. They are expressed as annual average weekday traffic flow and represent the 24 hour traffic volume passing through a site on a typical weekday (MRD 1986).

These individual grid values were summed to provide an overall measure of the recorded total daily VKT for Perth. Any shortfall between this figure and the estimated total VKT, listed in Table 7, can be attributed to subarterial roads. This was allocated across the region on the basis of the recorded traffic volumes.

Table 7

Estimated total VKT (Vehicle Kilometres Travelled) for Perth for 1985. Note weekend VKT is estimated at 1.5 average weekday VKT (after ABS 1985).

Vehicle Class	Total Annual VKT (10^9 km)	Equivalent average daily VKT (10^7 km)
Automobiles	6.996	2.064
Utilities/Panel vans	1.168	0.345
Total Motor vehicles	8.164	2.409
Trucks	0.445	0.131
Motor cycles	0.138	0.041
Total	8.747	2.581

The total truck VKT, given in Table 7, was allocated to high truck usage routes in the metropolitan area (Lyons *et al* 1987) on the basis of the total grid VKT and subtracted from the individual grid totals. As the truck driving cycle is independent of peak periods, the truck VKT was divided by 24 to represent an average hourly truck VKT.

24 hour VKT weightings for Perth are 16.5% morning peak (0700-0900), 18.5% evening peak (1600-1800) and 65% for all off-peak times (Kenworthy *et al* 1983). Consequently, the daily VKT for each grid square was corrected by these factors and divided by the length of the period to provide an hourly estimate of non-truck VKT.

The truck and non-truck VKT were then multiplied by the appropriate emission factors (Tables 4, 5), to provide an estimate of the total vehicle exhaust emission across the metropolitan area. Additional evaporative emissions are accounted for from the distribution of registered vehicles and added to the total for HC. Figure 1 illustrates the spatial variation of the calculated morning peak and off peak NO_x emissions. The major arterial roads are clearly visible as well as the increased emission during the morning peak period. Given the small variation in NO_x emission factors across the region, the major spatial variations are the direct result of variations in VKT. Similar maps were obtained for the other pollutant species.

Emission totals presented in Figure 1 are not directly verifiable as they are based on average traffic conditions across the metropolitan area, which are not necessarily observed on any one day. However they do indicate the spatial variation in source strength and provide an indication of the relative magnitude of pollutant sources in different regions. An alternative statistic can be obtained from Table 5 by computing the predicted CO/NO_x ratio on the basis of both time period and location (Table 8).

Table 8

Variation of CO/NO_x ratio across the Perth airshed resulting from temporal and spatial variation in driving patterns, where MP is morning peak, EP evening peak and OP off peak.

Region	CO/NO_x ratio MP 0700-0900	EP 1600-1800	OP
1. Central Core	11.5	11.8	10.1
2. Inner suburbs	10.2	10.3	9.2
3. Middle western suburbs	10.1	9.3	9.2
4. Middle south, outer north and eastern suburbs	9.9	8.9	8.8
5. Outer south east and north east suburbs	10.1	9.2	8.4
6. Northern state housing suburbs	8.7	8.9	8.9

The greater congestion and higher accelerations as you approach the CBD leads to an increase in the CO/NO_x ratio of pollutants emitted from the exhaust pipe. As both smog-chamber and computed results suggest that added CO accelerates the depletion of NO and the generation of NO_2 as well as enhanced generation of O_3 through NO_2 photolysis (Demerjian *et al* 1974, Drake *et al* 1979), the change in driving patterns brought about by increased congestion enhances smog formation, through increased CO generation per kilometre of travel. Given the increased concentration of vehicles using the CBD this becomes significant. If evaporative emissions are also included, the greater number of vehicles in the CBD would lead to a corresponding increase in HC emissions.

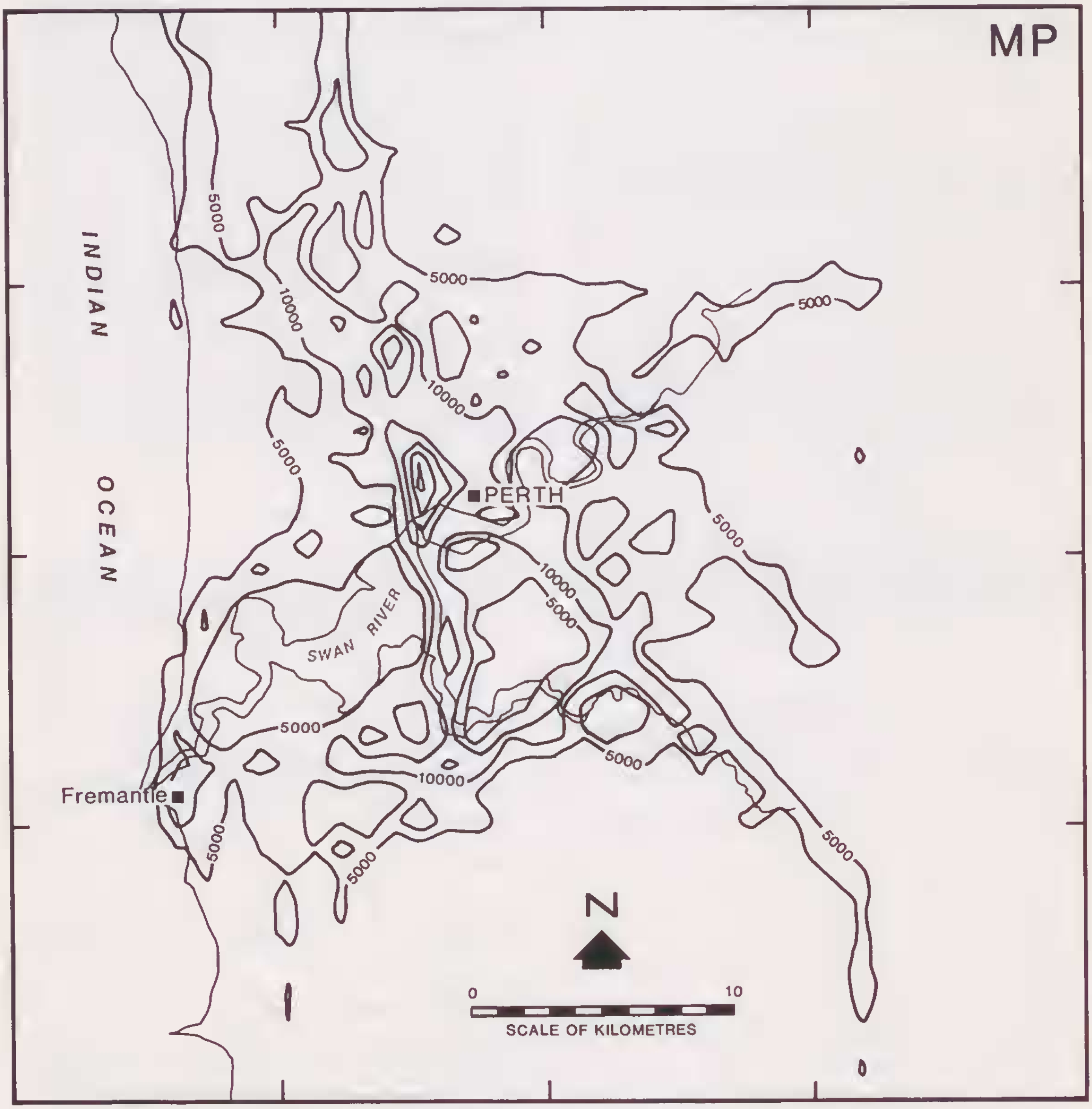
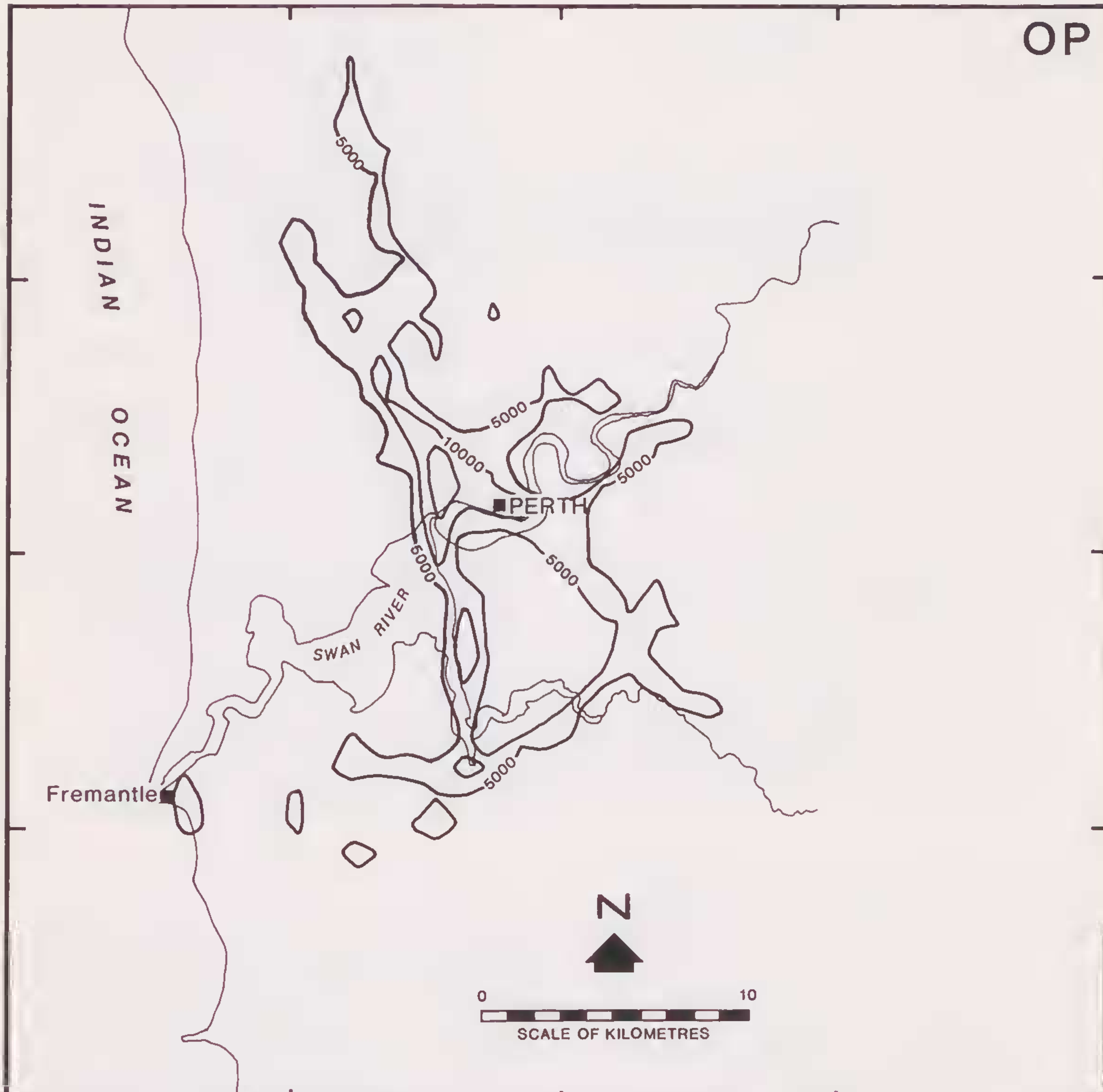


Figure 1 Predicted emission of NO_x (g hr^{-1}) across Perth for the morning peak (MP) and off peak (OP) periods.



Conclusions

The integration of driving characteristics and vehicle emissions based on speed and acceleration illustrates a marked variation in emission factors from the CBD to the outer suburbs. In particular, the greater congestion and corresponding variations in acceleration within the CBD, increases the production of pollutants and the potential for photochemical smog through enhanced CO production.

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